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Thermoprocessing and wire drawing behaviour of ultra high strength steel wires☆

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Summary The thermo-processing of piano wire rods is carried out in the lead bath. This experimentation is carried out under industrial conditions. The investigation is done to examine the effect of austenitic time, lead bath time and wire diameter on mechanical properties of lead patented wire. The Taguchi technique is adopted for optimization of thermo-processing of hypereutectoid steel wires. The lead patented wire of diameter 7.00 mm is cold drawn in a sequence of conical converging dies. The best pass schedule of lead patented piano wire is obtained by optimizing the ultimate tensile strength and torsion strength of cold drawn wire. The characterization of wire drawing behaviour of lead patented wires is carried out using optical microscopy, scanned electron microscopy and X-ray diffraction analysis techniques.

Introduction

The microstructure of hot rolled piano wire rods consist of coarse pearlite along with thick layers of cementite at grain boundary. This microstructure is not suitable for cold wire drawing process. Hence, thermo-processing of hot rolled piano wire rods (Han et al., 1993) is carried out to improve the mechanical and formability properties. Thermo-processing of hot rolled piano wire rods is carried out by using a lead patenting furnace (Bargujer et al., 2013; Kazeminezhad and Taheri, 2003). The heating zone and lead bath zone of furnace is 13 meters and 4 meters long respectively. The austenitic temperature in piano wire rods is achieved in heating zone. The phase transformation in piano wire rods took place in lead bath. During phase transformation, the microstructure of hot rolled piano wire rods changes into very fine pearlitic microstructure. The lot of study has been carried out on the interlamellar spacing

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Table 1 Experimental L_9 array with responses.

Expt. no.	Sample no.	Process input parameters			Process responses		
		T_a (min)	T_{pt} (s)	D_w (mm)	UTS (N/mm^2)	TS (nos. of turns)	RA (%)
1	a	5	5	7.00	1223.14	24	30.73
2	b	5	30	4.00	1275.54	19	25.93
3	c	5	90	2.50	1243.37	40	47.12
4	d	10	5	4.00	1131.78	15	28.76
5	e	10	30	2.50	1334.42	39	42.07
6	f	10	90	7.00	1005.07	34	24.84
7	g	20	5	2.50	1166.59	65	42.61
8	h	20	30	7.00	1156.33	30	29.45
9	i	20	90	4.00	1187.50	37	25.66

analysis (Elwazri et al., 2005; Zhang et al., 2011) in thermoprocessed hypereutectoid steel wire rods. However, the optimization of lead patenting process using Taguchi techniques is very limited. The orthogonal array L_9 is selected to study the effects of austenitic time, lead bath time and wire diameter on mechanical properties of lead patented wire rods. The cold wire drawing (Haddi et al., 2011; Bargujer et al., 2015) behaviour of lead patented piano wire rods is studied for improvement of microstructure and mechanical properties.

Material and methods

The piano wire rods are selected for the study which belongs to hypereutectoid steel. The chemical composition of piano wire rods is 0.87% carbon, 0.50% manganese, 0.18% silicon, 0.006% sulphur and 0.007% phosphorus. The experimentation is designed as per Taguchi's L_9 orthogonal array. The array has three process input parameters at three different levels. The L_9 array with obtained responses is mentioned in Table 1. The effect of austenitic time (T_a), phase transformation time (T_{pt}) and piano wire rods diameter (D_w) on ultimate tensile strength (UTS), torsion strength (TS) and reduction in area (RA) of lead patented wires is investigated under industrial conditions.The X-ray diffraction plot, optical micrograph and SEM micrograph of thermoprocessed piano wire rod is shown in Fig. 1. The constructive peaks in X-ray diffraction plot are produced by those atomic planes, which obey the condition that '$h+k+l$ = even'. The indexing of diffraction peaks in X-ray diffraction plot is done using structural factor equation. The optical micrograph as well as

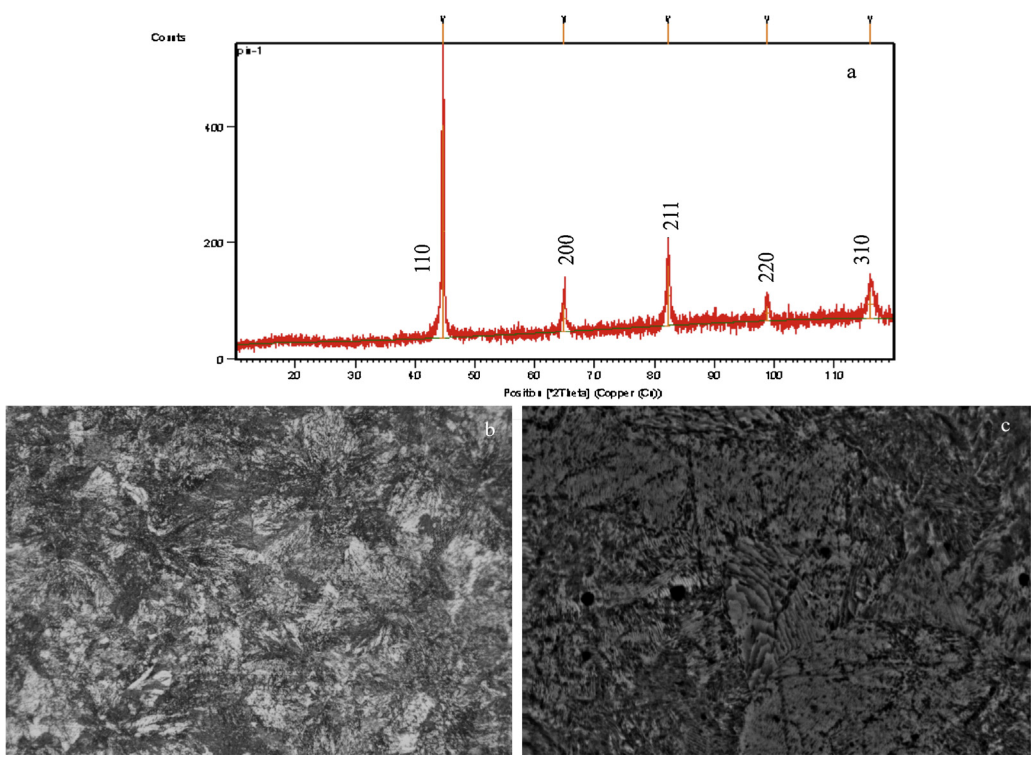

Figure 1 (a) X-ray diffraction plot, (b) optical micrograph and (c) SEM micrograph of thermoprocessed piano wire rod.

Table 2 The various pass schedules with mechanical properties.

Die no.	Pass schedule-1			Pass schedule-2			Pass schedule-3		
	D_w (mm)	UTS (N/mm^2)	TS (nos.)	D_w (mm)	UTS (N/mm^2)	TS (nos.)	D_w (mm)	UTS (N/mm^2)	TS (nos.)
0	7.00	1259.09	30 SFC	7.00	1259.09	30 SFC	7.00	1259.09	30 SFC
1	6.00	1437.16	28 SFC	6.00	1437.16	28 SFC	6.00	1437.16	28 SFC
2	5.00	1625.51	26 SFC	5.30	1516.90	48 SFC	5.60	1498.56	36 SFC
3	4.40	1715.32	38 SFC	4.70	1618.64	32 SFC	5.20	1560.43	42 SFC
4	3.80	1822.52	18 SFS	4.20	1733.41	42 SFC	4.80	1572.43	40 SFC
5	3.40	1889.50	44 DFS	3.80	1827.86	32 SFC	4.50	1634.16	28 SFC
6	3.00	2038.52	22 SFS	3.40	1939.85	18 SFC	4.20	1658.24	30 SFC
7	2.60	2195.65	23 DFS	3.10	1964.35	21 DFC	3.90	1741.11	30 SFC
8				2.80	1995.42	21 DFC	3.60	1851.48	32 SFC
9				2.60	2080.11	35 SFC	3.30	1905.31	16 SFC
10							3.00	1938.97	30 DFS
11							2.80	1975.62	35 DFS
12							2.60	2013.54	26 SFC

SEM micrograph indicates that the microstructure developed in thermoprocessed wire rod is very fine pearlite.

Results and discussion

The responses of lead patenting process i.e., UTS, TS and RA of thermo-processed wires are mentioned in Table 1 under column 'process responses'. The Analysis of Variance and response table for signal to noise ratios are calculated using Minitab 17. The 'larger is better' criterion is selected. The results of linear model analysis for SN ratios versus austenitic time, phase transformation time, wire diameter are as follows.

The analysis of variance predicts that the contribution of T_a, T_{pt} and D_w in UTS is 20.00%, 27.46% and 30.52% respectively. Similarly, the contribution of T_a, T_{pt} and D_w in TS is 27.98%, 5.35% and 56.16% respectively and the contribution of T_a, T_{pt} and D_w in RA is 2.04%, 0.80% and 93.02% respectively. The analysis of variance for SN ratios indicates that the overall contribution of T_a, T_{pt} and D_w in the mechanical properties is 11.94%, 3.27% and 82.73% respectively. The ranking of process parameters D_w, T_a and T_{pt} on the basis of signal to noise ratio for mechanical properties of lead patenting process is first, second and third respectively.

Die pass schedules

The die pass schedules are analyzed for optimization of UTS and TS of cold drawn wire. In this study, the lead patented wire of diameter 7.00 mm is cold drawn through different die schedules. The die sequences along with obtained mechanical properties are mentioned in Table 2. The pass schedule-1, pass schedule-2 and pass schedule-3 has high, medium and low reduction ratio per die respectively. The characteristic of fracture in torsion test may be single facture with clean surface (SFC), single fracture with split surface (SFS), double fracture with clean surface (DFC), double fracture with split surface (DFS). The split fracture surface indicates the loss of ductility by wire.

The first pass schedule results in high UTS as compared to second and third pass schedule but the TS is highly inferior. The third pass schedule results in low UTS as compared to first and second pass schedule but the TS is inferior as compared to second pass schedule and superior as compared to third pass schedule. The numbers of die in third pass schedule also increases drastically. This result in more manpower required for obtaining inferior mechanical properties as compare to second pass schedule. The second pass schedule results in ultra high strength cold drawn wires with high ductility. Hence, the second pass schedule is best pass schedule to obtain optimum mechanical properties.

The study of stereo microscopic images of fracture surfaces in UTS test and torsion test for all three passes was carried out. The images of fracture surfaces for pass schedule-1 predict that material becomes highly brittle after drawing to 2.60 mm. The images of fracture surfaces for pass schedule-3 predicts that material has good ductility after drawing to 2.60 mm but UTS is low as compared to pass schedule-2 and -3. The images of fracture surface of pass schedule-2 predict that high ductility is achieved even with ultra high UTS when drawn to 2.60 mm.

Conclusions

The experiments on thermoprocessing of hypereutectoid steel wires are designed using Taguchi's L_9 orthogonal array and the results of analysis of variance are obtained. The best die pass schedule is obtained by optimizing UTS and TS. The conclusions are drawn as:

a) The austenitic time, phase transformation time and wire diameter contributes 20%, 27% and 30% in UTS of thermo-processed wires.
b) The austenitic time, phase transformation time and wire diameter contributes 28%, 5% and 56% in TR of thermo-processed wires.
c) The austenitic time, phase transformation time and wire diameter contributes 2%, 1% and 93% in RA of thermoprocessed wires.

d) The responses are highly affected by wire diameter, followed by austenitic time and phase transformation time.
e) The analysis of microstructure by optical, SEM microscopy and X-ray diffraction reveals that the microstructure developed in thermoprocessed wires is very fine pearlitic structure and best suitable for cold wire drawing process.
f) The die pass schedule-2 results in production of wires with ultra high strength and high torsion strength.

Future prospective

The characterization of cold drawn wires by SEM and TEM microscopy using different die pass schedules may lead to explanation of exact mechanism of loss of ductility.

Conflict of interest

The authors declared that there is no conflict of interest.

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